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Ship domain applied to determining distances for collision avoidance manoeuvres in give-way situations

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A R T I C L E I N F O

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A B S T R A C T

Ship domain is often used in marine navigation and marine traffic engineering as a safety condition. The basic idea behind those applications is that an encounter of two or more ships can be considered safe if neither of ship domains is intruded by other ships. Research utilising this approach has been documented in numerous works, including publications on optimising collision avoidance manoeuvres performed to fulfil domain-based safety conditions. However, up to this point there has been no method, which would apply ship's domain to determine the last moment when a particular collision avoidance manoeuvre can still be successfully performed. This issue is addressed here. The proposed method uses a model of ship's dynamics to assess the time and distance necessary for a manoeuvre resulting in avoiding domain violations in give-way situations. The model and the method are described in detail and illustrated in a series of simulation results. The simulations cover full spectrum of typical give-way encounters in various circumstances: head-on, crossing and overtaking situations; manoeuvres limited to course alteration and those combining turns with speed reduction; open or confined waters and finally – in good and restricted visibility.

1. Introduction

A ship domain has been first introduced in (Fujii and Tanaka, 1971), where it has been defined as "*a two-dimensional area surrounding a ship which other ships must avoid*". Ever since then, ship domain concept has been used in maritime research, including recent applications to various traffic engineering-related problems: waterway capacity analysis (Liu et al., 2015), waterway collision risk analyses (Goerlandt and Kujala, 2014; Goerlandt and Montewka, 2015; Qu et al., 2011; Weng et al., 2012) and AIS-based near-miss detection (van Iperen, 2015; Wu et al., 2016; Zhang et al., 2016; Van Westrenen and Ellerbroek, 2017). However, it is collision avoidance that is arguably main purpose for ship domain's development (Pietrzykowski, 2008; Pietrzykowski and Uriasz, 2009; Hansen et al., 2013; Wang and Chin, 2015; Szlapczynski and Szlapczynska, 2017) and, as evidenced by some works, it still remains its important field of application (Szlapczynski, 2008; Lazarowska, 2016). Those applications of ship domain are based on the assumption that an encounter of two or more ships can be considered safe if neither of ship domains is intruded by other ships. However, up to this point there has been no method, which would combine ship's manoeuvrability and ship's domain to determine the last moment when a particular collision avoidance manoeuvre can still be successfully performed. This issue is addressed in the hereby paper. The presented method uses a model of ship's dynamics to assess the time and distance necessary for a manoeuvre successful in terms of avoiding domain violation. The method is inspired by action area presented in (Dinh and Im, 2016), critical range and time researched in (Hilgert and Baldauf, 1997) and critical distance introduced in (Krata and Montewka, 2015) and later extended in (Krata et al., 2016).

The rest of the paper is organized as follows. Related works and method's genesis are discussed in Section 2. The method is outlined in Section 3, which also includes description of its key algorithms. The applied ship dynamics' model is given in Section 4. Section 5 provides results obtained for an example ship. These results cover typical ship encounters in various circumstances: head-on, crossing and overtaking situations; manoeuvres limited to course alteration and those combining turns with speed reduction; open or confined waters and finally – good and restricted visibility. Results are discussed in Section 6, followed by the summary and conclusions given in Section 7.

2. Related works and the current method's genesis

Most of collision avoidance research is focused on manoeuvres done in advance, with enough time for optimisation (Kao et al., 2007; Tam

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et al., 2009; Tsou et al., 2010; Praczyk, 2015; Zhang et al., 2015; Tsou, 2016; Pietrzykowski et al., 2017). In comparison, there are relatively few works on when exactly a manoeuvre should be performed to achieve safe separation. The concept of an arena – an evasion area around a ship was first outlined in (Davis et al., 1980) and later developed in (Colley et al., 1983). Close quarters term was defined in (Hilgert, 1983), where the author observed that COLREGS (Cockcroft et al., 2012) do not give specific distances, where an evasive action is necessary. Such limit values, at which the navigator has to order the evasive actions were determined in (Hilgert and Baldauf, 1997) and the approach presented there was later applied in an on-board Manoeuvring Support System (Baldauf et al., 2014). Similarly, in (Zhang et al., 2012) a study on minimum distance for escape action was presented, based on an analysis of an encounter scenario. Following this, in (Dinh and Im, 2016) a combination of analytical approach with utilising expert navigators' knowledge was applied to determine a ship's action zone. However, the limitation of the above research was either the limited number of encounter scenarios taken into account or simplified modelling of ship's manoeuvres. Those limitations were overcome in (Krata and Montewka, 2015). Those authors were interested in determining the last moment, when collision could still be avoided by manoeuvres of the own ship alone. Their research involved a detailed analysis of the own ship's evasive action, which included precise prediction of the own trajectory based on the manoeuvrability parameters. The method was further extended in (Krata et al., 2016), where, among others, stability issues were taken into account (avoidance of excessive heel) (Matusiak and Stigler, 2012). The final result of both versions of this method was a critical distance between the own ship and a target ship determined for a given encounter situation. This critical distance represented the last moment when a manoeuvre had to be performed to avoid collision. The method was dedicated to situations, when the own ship was a stand-on one, which generated some additional assumptions. Among others, a resulting, near-zero separation between ships was assumed there for simulations. In practice, a manoeuvre would have to be initiated earlier (sometimes much earlier) if a larger ship separation is supposed to be kept.

The current paper is inspired by (Krata and Montewka, 2015) and the works of their predecessors, but the central idea of that paper is here combined with a ship domain model: we are interested in a distance and time to potential collision, which still make it possible to avoid violation of a specified ship domain. Additionally, the collision avoidance action is supposed to fulfil a number of configurable conditions dictated either by COLREGS or by a navigator. For a given encounter situation a considered turn should:

- be made to starboard or port only, depending on the particular encounter and visibility conditions,
- not exceed a given angle of rudder.

3. The method's overview

Contrary to (Krata and Montewka, 2015; Krata et al., 2016) the current method is mostly dedicated for situations when own ship is the give-way ship. While COLREGS specify what action should be taken depending on the encounter type, it is up to the navigator of the own ship to decide when exactly to perform a manoeuvre. This decision may depend on the intended separation, which is represented here by a ship's domain.

A scheme of the method's main algorithm, is given in Fig. 1. The method applies a degree of domain violation (DDV) – a parameter indicating to what extent a ship's domain will be intruded during a close quarters situation (Szlapczynski and Szlapczynska, 2016).

In brief, the method works as follows. It reads the necessary input parameters and detects potential domain violations. If a domain violation is predicted based on the current data, the encounter situation is classified and the action type is chosen. For a chosen action type and

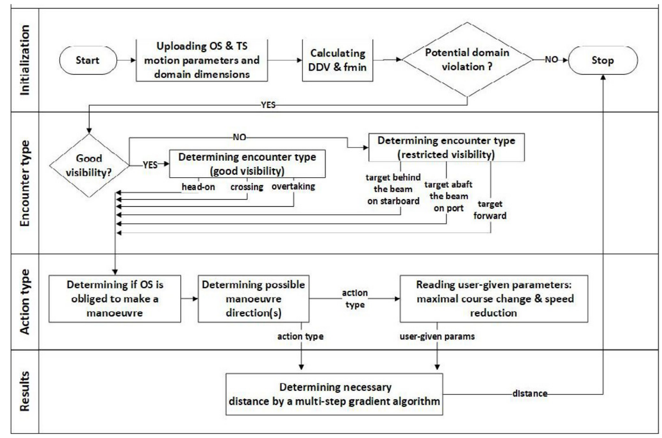

Fig. 1. A method determining time and distance necessary for avoiding domain violations.

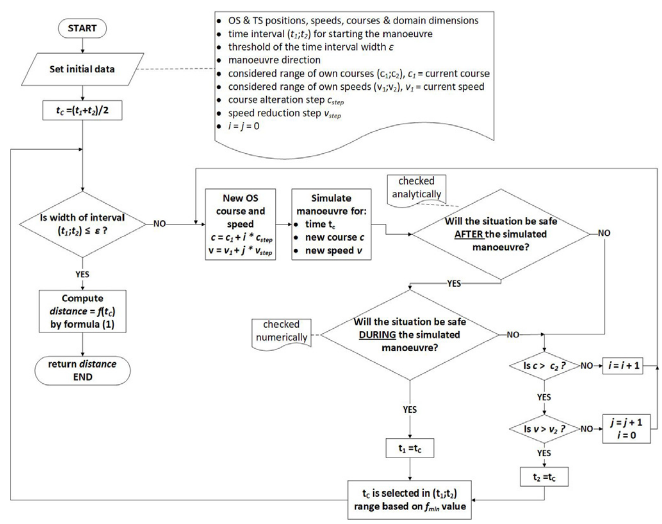

Fig. 2. A multi-step gradient algorithm determining safe time, at which a manoeuvre should be initiated.

auxiliary user-specified parameters, the method determines the time for initiating the manoeuvre by means of a gradient algorithm, which is shown in Fig. 2.

The gradient algorithm (Fig. 2) works as follows. At first a set of initial parameters is read, comprising of both ship parameters (including positions, speeds and courses and threshold for the time range ε) and action type parameters (including manoeuvre direction and ranges of considered course and speed alterations). Then a candidate time t_c is introduced and initialized. The algorithm detects potential domain violations of a manoeuvre initiated at time t_c. Domain violations are checked during and after performing the manoeuvre. Because the latter might be done analytically (meaning faster computations), "after manoeuvre" check is performed before "during manoeuvre" check. Depending on whether the manoeuvre done at t_c is safe or not, the considered time range is narrowed up to or down to t_c. A new t_c value is then selected from the updated (t_1,t_2) range based on the results of domain violation check and the simulation is repeated. The algorithm ends, when the range (t_1;t_2) gets smaller than the threshold value ε. Once the action time t_c is determined (Fig. 2), the action distance is computed according to formula (1) and returned by the algorithm:

$$d(t_c) = \sqrt[2]{V_r t_c + 2\left(V_{r_x} X_r + V_{r_y} Y_r\right) t_c + X_r + Y_r} \tag{1}$$

where:

$d(t_c)$ – action distance as a function of action time,
t_c – action time,
X_r –x component of the target's initial relative position,
Y_r – y component of the target's initial relative position,
V_r – target's relative speed,
V_{rx} – x component of the target's relative speed,
V_{ry} – y component of the target's relative speed.

Computed action distance is then further used in the algorithm depicted in Fig. 1. In general the method's functional scope is limited to determining the distance and time at which the specified manoeuvre (preferred by a navigator) should be performed in order to avoid domain's violation. The manoeuvre's parameters – the maximal size of course change and (optionally) speed reduction – are assumed to be set by a navigator. A separate complementary decision support tool enabling the navigator to choose a particular manoeuvre has been presented by the authors in (Szlapczynski and Szlapczynska, 2015).

4. Model OF SHIP'S manoeuvrability used in the method

The model ship taken into account is a mid-size ro-pax, whose particulars are as follows (Table 1).

A Matlab script has been prepared to perform the simulation of the model ship dynamics. The applied model comprises the following: ship's initial speed and her inertia, time for gradual reduction of the propeller thrust, simple formula for calculation of the hull resistance dependent on ship's speed. It was assumed that the ship steaming with service speed equal 17 knots for 100 s is followed by 120 s of the dropping power supply to the propeller. The thrust gradually decreases to the value corresponding to the speed 8 knots, which still enables to control the course with the use of a rudder. However, the ship is pushed forward by her inertia besides the propeller thrust, so the decrease in speed is slower than the thrust reduction, which is assumed a realistic scenario. The result of the simulation is presented in Fig. 3.

As it may be clearly seen in Fig. 3 the reduction of ship speed alone cannot be found as time-efficient manoeuvre. However, speed reduction of the model ship is considered in the research flexible enough to be an additional manoeuvre supporting course alternation. According to the result of the performed simulations the ship slowing down characteristics is presented in further computations in the form of a meta-model as follows:

$$V_t = \sum_{i=1}^{9} s_i \cdot t^{i-1} \tag{2}$$

where:

s_i – coefficients of the polynomial model and
t – the time from the speed reduction manoeuvre initiation.

Since there are numerous factors influencing practical manoeuvring characteristics of the ship we utilize LaiDyn software (Matusiak, 2013). The tool is capable to simulate in time domain motions of a ship in six

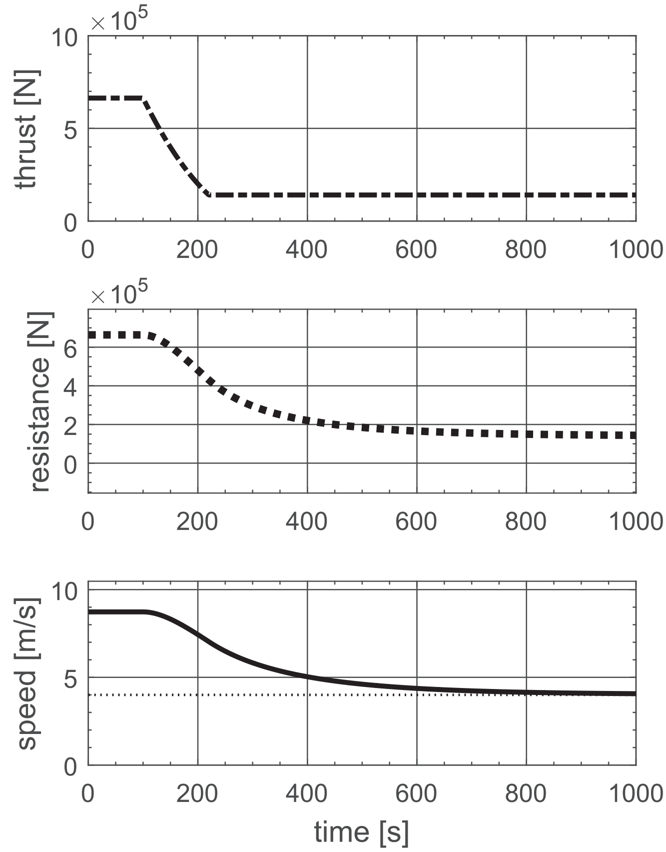

Fig. 3. Simulation of the slowing down process for the model ship; history of thrust, resistance and resulting speed reduction.

degrees-of-freedom with regard to her shape, rudder and propulsion action and the action of wind and wave in irregular seas conditions. LaiDyn is based on a panel method and Froude-Krylov force is modelled in nonlinear approach along with diffraction and refraction forces. The rudder force is also calculated on the basis of the rudder profile and water flow conditions. As a result, not only ship inertia is taken into account but also very detailed distribution of friction and pressure field surrounding the hull is considered, including sea wave action and hull's generated wave system action as well. The ship rolling, pitching and heaving is included to the force balance and energy balance calculations. The mathematical formulation remaining behind LaiDyn is as follows:

$$\begin{aligned} \frac{du}{dt} &= \frac{X_{prop} + X_{resist} + mrv}{m - X_{\dot{u}}} \\ \frac{dv}{dt} &= \frac{-mru + Y_v v + Y_r r + Y_{\dot{r}} \dot{r} + L}{m - Y_{\dot{v}}} \\ \frac{dr}{dt} &= \frac{N_v v + N_r r + N_{\dot{v}} \dot{v} + 2\dot{L} L_{pp}}{I_{zz} - N_{\dot{r}}} \end{aligned} \tag{3}$$

where:

u – the linear velocity along axis X;
X_{prop} – the propeller thrust;
X_{resist} – the ship resistance;
m – the ship mass;
r – the angular velocity along axis Z;
v – the linear velocity along axis Y;
L – the lift forces on the rudder;
L_{pp} – the length of the ship between perpendiculars;
I_{zz} – a mass moment of inertia;
$X_{\dot{u}}$, Y_v, Y_r, $Y_{\dot{r}}$, $Y_{\dot{v}}$, N_v, N_r, $N_{\dot{v}}$, $N_{\dot{r}}$ – hydrodynamics derivates.

The detailed description of the LaiDyn code is available in

Table 1
Parameters of the ro-pax model ship.

Parameter name	Parameter value
Length between perpendiculars *LBP* [m]	158
Breadth *B* [m]	25
Draft *d* [m]	6.10
Hull height *H* [m]	15
Displacement *D* [t]	14152
Wetted surface *S* [m^2]	4356
Block coefficient *CB* [-]	0.571
Initial metacentric height *GM* [m]	1.90
Service speed *Vs* [kn]	17

(Matusiak, 2007, 2013). The state-of-the-art LaiDyn code satisfactorily passed numerous ITTC benchmark tests (ITTC, 2002; ITTC, 2005) and has been found a reliable simulation tool. Moreover, even the rudder and propeller thrust is directly modelled instead of typical simple attaching of a virtual (usually arbitrary set up and fixed in time) thrust force which is quite common. Thus, the top quality model of the ship dynamics is utilized in the study which allows for covering of all key hydrodynamic phenomena.

In this study the LaiDyn code is utilized to obtain the time histories of the considered ro-pax circulations with regard to her 6DoF motions, similarly to the former work (Matusiak and Stigler, 2012). The rudder angle is assumed consecutively to 10, 20 and 30° to port and to starboard to obtain the set of trajectories. In order to observe noticeable effects of seas action, the weather conditions taken into account in simulations are quite heavy, e.g. the wind force is set 8B and the corresponding Jonswap wave spectrum is considered.

The numerical simulations of 6DoF ship motions provide the time history of coupled motions (with regard to the ship characteristics influencing all degrees-of-freedom). However, for further use in evasive manoeuvre planning procedure the shape of ship tracks are essential. These trajectories obtained for every single studied case are represented by a set of relative positions in consecutive time steps (t_i, X_i, Y_i) where X_i and Y_i denote the position of ship's centre of gravity referred to the initial position fixed at the manoeuvre commencing. Sample trajectories for the model ship are shown in Fig. 4.

The obtained set of simulation results for the model ship turning to port and to starboard comprises the full range of rudder settings reaching from $-30°$ up to 30°. As the irregular seas are taken into account the result of a simulation is non-deterministic, so every single case is repeated three times and averaged at the post-processing stage. The obtained trajectories are generalized in the form of a meta-model consisting in three formulas enabling calculation of ship's centre of gravity relative position in every moment of the turning manoeuvre and the relative heading. The relative position and the relative heading refer to the initial position and the initial heading of the ship at the manoeuvre commencing. The 5-th and 6-th order polynomial power series constituting the meta-model are as follows:

$$X_t = \sum_{i=1}^{6} p_i \cdot t^i \ ; \quad Y_t = \sum_{i=1}^{6} q_i \cdot t^i \ ; \quad heading\_rel_t = \sum_{i=1}^{5} r_i \cdot t^i \tag{4}$$

where:

X_t, Y_t – the modelled position of ship's centre of gravity (referred to the initial position fixed at the manoeuvre commencing) at any time moment,

$heading\_rel_t$ – the relative heading at any time moment, taking the initial heading at the manoeuvre commencing as zero,

t – time of the turning manoeuvre (continuous variable in the meta-model),

p_i, q_i, r_i – the model coefficients adjusted with the use of least squares method.

Two meta-models has been worked out in the course of this study, namely:

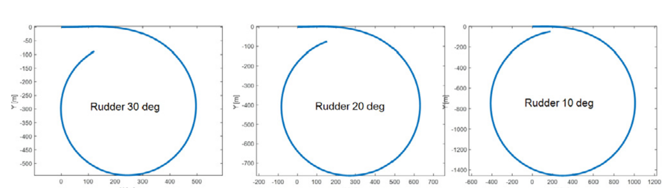

Fig. 4. Sample trajectories of considered ship for rudder setting 30, 20 and 10° to starboard obtained in the course of LaiDyn 6DoF simulations.

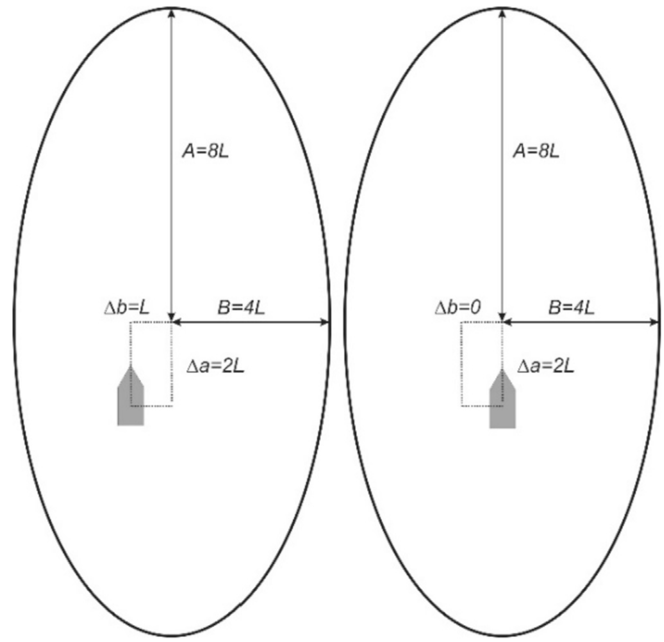

Fig. 5. Length-dependent ship's domains applied in the simulations: left – for head-on and crossing encounters, right – for overtaking.

– the speed reduction model without ship course alternation,
– the turning model without supplied power reduction (only natural speed reduction due to circulation exists).

Both models allow for time-efficient computations at the stage of collision manoeuvre planning. It must be emphasised that the full set of ship motion simulations has to be carried out once only and does not need to be repeated on board, which is vital in terms of possible application. In future research the ship dynamics model may be extended so as to cover ship's behaviour in severe weather conditions and stability-related issues (Wawrzyński and Krata, 2016a), (Wawrzyński and Krata, 2016b), (Krata and Wawrzyński, 2017a), (Krata and Wawrzyński, 2017b).

5. Method's simulation results

This section contains results of simulation experiments carried out to determine the boundary line around the own ship, which should not be intruded by a target ship if neither of the ships' domains (own ship's domain as well as target ship's domain) are to remain unviolated. The domains shown in Fig. 5 have been applied for head-on and crossing encounters (left) and for overtaking encounters (right). The domains' decentralised elliptic shapes were first proposed in (Coldwell, 1983), but the dimensions used here have been updated so as to be in line with more recent research in the field based on empirical data (Hansen et al., 2013; Wang and Chin, 2015).

Throughout all test scenarios the model of the own ship from Section 4 has been used to generate boundary lines defining ship's arena (Davis et al., 1980; Colley et al., 1983). The own speed is set to 17 knots for all scenarios, unless speed reduction is applied and discussed. As for rudder deflection in case of course alteration manoeuvres, a 10° rudder deflection has been applied for turns of up to 60° and a 20° rudder deflection for turns larger than that. This choice has been dictated by the model of the selected own ship: for standard turns of up to 60°, a small rudder deflection is sufficient to change course quickly. As for large turns, a larger rudder deflection is justified to shorten the manoeuvre's execution time, however truly large rudder deflections should normally be avoided because of stability-related phenomena, especially when navigating in harsh weather. Throughout the simulations normal

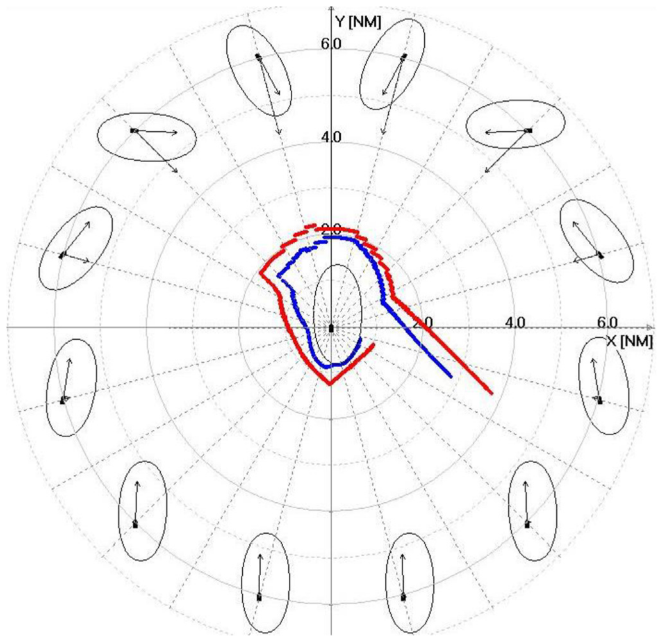

Fig. 6. Own ship's arenas for a target ship approaching with a true speed of 18 knots (blue line) or 25 knots (red line) in good visibility. Course alterations of up to 90° and no speed reduction are assumed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

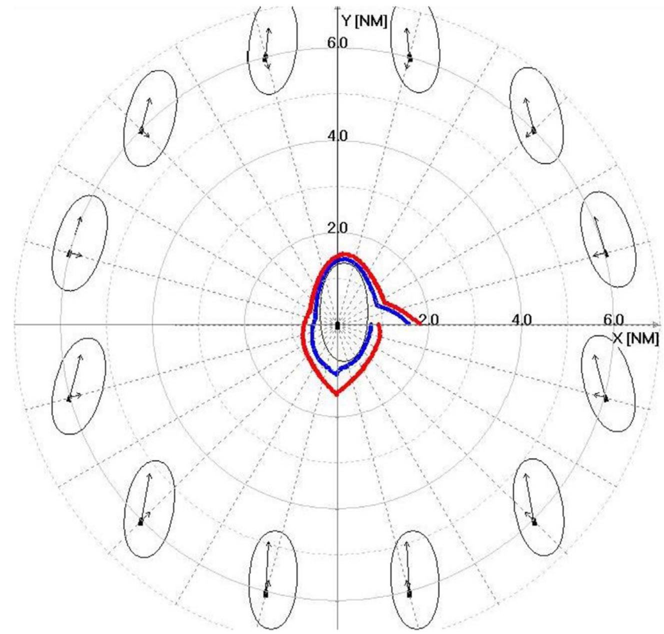

Fig. 7. Own ship's arenas for a target ship approaching with a relative speed of 5 knots (blue line) or 12 knots (red line) in restricted visibility. Course alterations of up to 90° and no speed reduction are assumed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

weather conditions are assumed, so as to isolate the action lines' dependency on the chosen evasive manoeuvre and its volume.

5.1. General results obtained for good and restricted visibility conditions

It has been assumed that a single target ship approaches the own ship from various relative bearings with the same true speed or the same relative speed. For target ship's positions granularity of 0.05° has been applied in each simulation, which means that 7200 target ship's relative bearings have been used to generate a full action line around the own ship. All target ships have been placed at 6 NM distance from the own ship. As for the courses of the target ships they have been automatically set to values, which would result in DCPA equal to 0 and degree of domain violation (DDV) equal to 1. It must be mentioned here, that setting target ships' courses to different values would obviously affect the obtained results.

Selected 12 of the above mentioned 7200 target ship's positions are shown in Fig. 6 (results for good visibility) and Fig. 7 (results for restricted visibility). A fixed true speed of a target ship has been applied by default for various relative bearings of a target ship. However, in some cases the same true speed did not allow to generate appropriate encounters for all considered relative bearings, so the fixed relative speed was used as an alternative when determining ships' arenas. The two different approaches are shown in Fig. 6 (fixed true speed for various relative bearings of a target ship) and Fig. 7 (fixed relative speed for various relative bearings of a target ship), where arenas are determined for good and restricted visibility, respectively. Applying fixed relative speed for the restricted visibility case makes it easier to simulate smaller values of relative speeds, at which ships should approach each other in restricted visibility.

In Fig. 6 a target ship's true speeds of either 18 knots (blue line) or 25 knots (red line) have been assumed. Target ship's speed smaller than 18 knots would not make overtaking possible and the full arena could not be generated. For Fig. 7 target ship's relative speeds of either 5 knots (blue line) or 12 knots (red line) have been assumed. To illustrate both overtaking and being overtaken, a relative speed of a target ship had to be used in Fig. 7, because the same true speed of a target ship obviously does not allow for both overtaking and being overtaken. True speed vectors are marked parallel to target ships' domains. As can be seen, the arenas' boundaries are not continuous, because different COLREGS rules begin to apply at some relative bearings. In case of good visibility (Fig. 6), the situation becomes classified as crossing for a relative bearing of 22.5° behind traverse, so only manoeuvres to starboard are considered. For restricted visibility (Fig. 7), only turns to starboard are considered for target ships in front of the own ship, unless they are to be overtaken. In both cases manoeuvres to starboard for target ships behind the traverse or near the traverse on starboard side require much earlier action. As a result the arena's line is more distant from the own ship's domain in the behind-the-traverse part of the starboard sector (Fig. 6) or near-traverse part (Fig. 7).

For both Figs. 6 and 7 course alterations of up to 90° only were considered and speed reduction manoeuvre was not taken into account. It must be emphasised here that the arena (action line) depends strongly on the maximal course alteration and maximal speed reduction, which are acceptable from the navigator's point of view. Maximal acceptable course alteration may be dictated by either navigator's preferences or limitations of a waterway. As for reducing own speed, this manoeuvre may be undesired in case of some engines, so the maximal speed reduction parameter should also be set by a navigator and in some cases it will significantly affect the action distances. The abovementioned and other tendencies will be investigated in detail in the following sub-sections dedicated to various types of ship-to-ship encounters.

5.2. HEAD-ON encounters

Own ship's action lines for head-on encounters are presented below. In Fig. 8 action lines for target ships of various true speeds are shown, assuming that the encounter takes place in limits sea room conditions and manoeuvres of up to 15° only are possible. As can be expected, the faster the approaching target ship, the earlier the own action is needed. In case of a target ship, whose true speed is 20 knots, the action is needed, when the distance is about 4 NM. For slower target ships, the

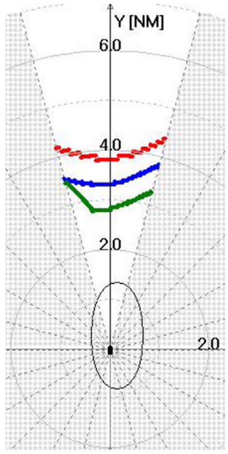

Fig. 8. Action lines for a target ship approaching head-on with a true speed of 10 knots (green), 15 knots (blue) or 20 knots (red) in a narrow channel or traffic lane. Course alterations of up to 15° and no speed reduction are assumed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

action can be started at about 3 NM from target ship. The action-triggering lines are not symmetrical, because manoeuvres to starboard only are considered and the domain itself is not symmetrical either. The asymmetry is especially evident for slower target ships, when the action is started later and the own dynamics and domain's shape heavily affect the results.

In Fig. 9 the action lines are shown for various sizes of course changes: 15, 30 and 60° to starboard. As can be seen, the action has to be initiated much earlier for course changes limited to 15°. The distance can be reduced nearly by half, if turns up to 30° are possible. Larger turns bring relatively little difference in the action distance. Also, as has been investigated, speed reduction does not affect the results significantly and is not a recommended option in this case. It must be noted however, that the latter can be attributed to the own ship's model, which allows for very fast turns and relatively more consuming speed reduction.

5.3. Overtaking

In case of overtaking it has been decided to use relative speeds in simulations, because a small true speed of a target ship makes it nearly

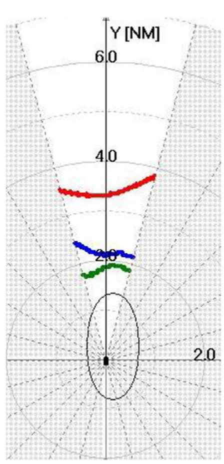

Fig. 9. Action lines for a target ship approaching head-on with a true speed of 15 knots. Assumed turns are 15° (red), 30° (blue) or 60° (green). No speed reduction. is assumed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

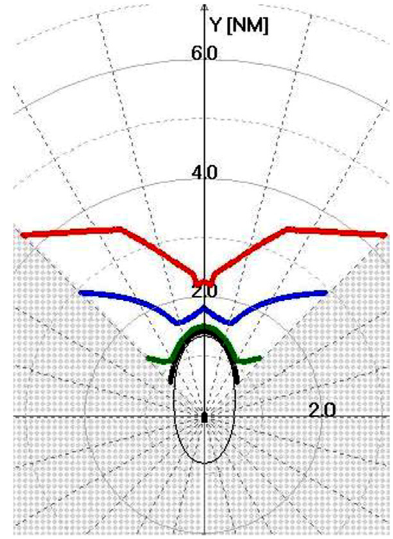

Fig. 10. Action lines for overtaking a target ship, whose relative speed is 4 knots (black), 8 knots (green), 12 knots (blue) or 16 knots (red). Assumed are turns by 15° to either side. No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

impossible to generate appropriate encounters for more distant relative bearings. Manoeuvres to either port or starboard are allowed when overtaking and the results for this case are provided in subsection 5.3.1. In some cases, however, manoeuvre to one side only is possible due to presence of obstacles or some other limitations. Therefore results for manoeuvres to port are additionally presented in subsection 5.3.2. As for manoeuvres to starboards, the results would be nearly mirror images of those to port (minor differences appear because of slightly different dynamics of turns to starboard and port), so they are not shown.

5.3.1. Manoeuvres to either side

The basic action-triggering lines are visualized in Fig. 10. For small relative speeds the own ship can avoid domain violation by a 15° turn done even at the very last moment. As expected, much earlier reaction is needed for larger relative speeds, up to 4 nautical mile distance in case of approaching a target ship with the unlikely relative speed of 16 knots. The distance gets larger for larger relative bearings: it is much easier to avoid a target ship directly in front than further on the side. When larger turns are applied (Fig. 11), the distance can be reduced from nearly 3 NM to about 1.5 NM (for a relative speed of 12 knots). Speed reduction however brings little gain in terms of reducing the action distance: for target ships on more distant relative bearings, the distance can be shortened from about 2.8 NM to 2.5 NM, which is shown in Fig. 12. Blue parts in Fig. 12 mark progress achieved by speed reduction, when compared to action line obtained for course alteration only (marked in red). In case of overlapping lines of different colours, the red line is always shown on top, followed by blue, green and black lines. As a result, for partly overlapping action lines only differences between them are shown.

5.3.2. Manoeuvres to one side only

Avoiding domain violation gets significantly harder if small turns to one side only (e.g. to port) are possible and the target ship is on that side (Fig. 13). For relative bearings nearing 45° the action distance ranges from about 2.5 NM for relative speed of 4 kn. to 5.5 NM for relative speed of 16 knots. Fortunately, larger turns can reduce the distance to about 4.5 NM in the worst case and to 2.5 NM or less for all other cases (Fig. 14). If such turns are not possible, than speed reduction is a reasonable alternative (Fig. 15): the action distance can be

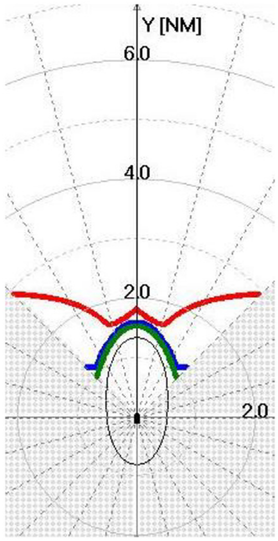

Fig. 11. Action lines for overtaking a target ship, whose relative speed is 12 knots. Assumed are turns of 15° (red), 30° (blue) and 60° (green) to either side. No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shortened to about 3.5 NM when reducing own speed by 3 kn. or to 3 NM when reducing by 6 kn.(further speed reduction brings little gain).

5.4. Crossing

Encounters with a target ship, whose true speed is 18 knots have been investigated throughout this subsection. Rule 15 of COLREGS states that the give-way ship should avoid crossing ahead of the other ship, which in this case means avoiding turns to port. A turn of 75° to starboard has been found the minimal one, which still made it possible to avoid domain violation for target ships behind the traverse on starboard, however the manoeuvre would have to be initiated at a distance of about 4.5 NM. Larger turns enabled actions at shorter distances: about 2.8 NM for 90°, 1.5 NM for 120° and 1 NM for 150° (Fig. 16). A combination of course alteration and speed reduction has occurred to be a useful alternative to large turns (Fig. 17): the same 75° turn makes it possible to act at a 2.6 NM distance when combined with a reduction of speed by 3 knots. A reduction by 6 knots may reduce the action distance to less than 2 NM and the gain is the largest in case of target ships far behind the traverse. Speed reductions by more than 6 knots are not justified, as they cannot effectively shorten the action distance.

It is worth noting that much smaller turns are sufficient in case of a target ship in front, even though the same true speed of a target ship (18 knots) results in larger relative speed. Manoeuvres of only 20° to starboard are sufficient to avoid domain violation, if initiated at 6.5 NM distance from the target ship. By enlarging the turn to 30, 45 or 60° the distance can be reduced to 4.1 NM, 2.6 NM and 1.9 NM respectively (Fig. 18). A turn by 20° combined with speed reduction may reduce the action distance to 5 NM or 4.2 NM in case of reductions by 3 or 6 knots respectively (Fig. 19). Larger speed reductions do not bring significant gain.

5.5. Restricted visibility

In restricted visibility manoeuvres to starboard are recommended for all target ships in front of the own ship. This makes it particularly hard to avoid domain's violation in case of fast approaching target ships on port (Fig. 20). The action distance values rise to about 5 NM for relative bearings of 50–55° and manoeuvres up to 45°. This can be attributed to the fact that turning by 45° to starboard makes the courses of both ships nearly parallel, so the own ship needs a larger turn to escape

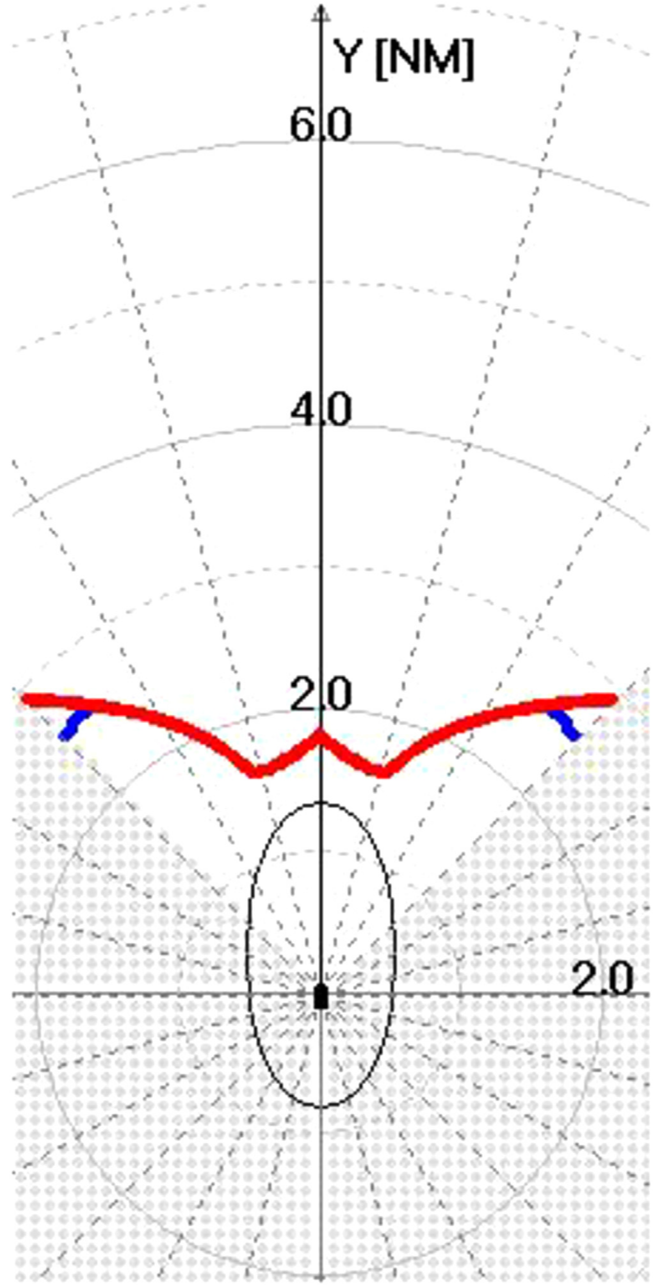

Fig. 12. Action lines for overtaking a target ship, whose relative speed is 12 knots. Assumed are turns of 15° to either side without speed reduction (red) or with speed reduced by 9 knots (parts, which are differ marked in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the faster target ship. Indeed, the action distance falls rapidly to 3 NM and less if manoeuvres up to 60° are considered. Larger turns however bring smaller progress and it takes a 90° turn to reduce the distance to 2 NM. The action line has a less dramatic shape on starboard side, where a 4.5 NM action distance is needed in case of 45° turn for a target ship on traverse. (Again the action distance can be easily shortened to 3 NM and less for larger turns.)

As for speed reduction, it can shorten the action distance to 3–4 NM for the worst cases of target ships on port and to about 2–3 NM for target ships on far starboard near traverse (Fig. 21).

In case of being overtaken by a target ship in restricted visibility a turn away from the target ship is recommended. This, combined with a small relative speed makes it much easier to avoid domain violation:

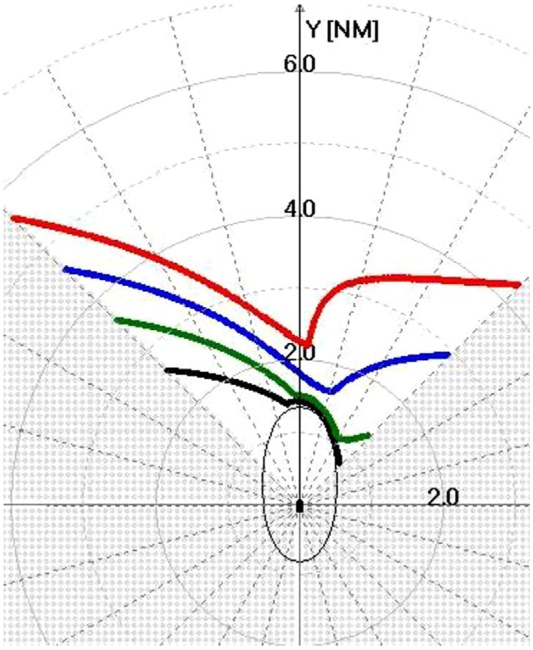

Fig. 13. Action lines for overtaking a target ship, whose relative speed is 4 knots (black), 8 knots (green), 12 knots (blue) or 16 knots (red). Assumed turns are 15° to port. No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

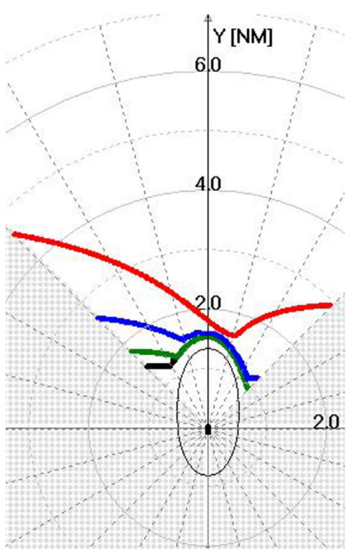

Fig. 14. Action lines for overtaking a target ship, whose relative speed is 12 knots. Assumed are turns to port by 15° (red), 30° (blue) and 60° (green). No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

smaller turns or shorter action distances are sufficient (Fig. 22). A turn of 15° is sufficient for a target ship behind on near parallel course. The same turn, however is not enough for target ships near traverse – the own manoeuvres would have to be made extremely early. Enlarging the size of a turn brings consequent progress – shortening the action distance to 3.5 NM for 30° and about 1 NM for 45°. Similar results can be obtained by a combination of course alteration and speed reduction (Fig. 23): the action distance can be shortened to 3.2 NM if a 6-knot reduction is combined with a turn by 15°. The latter is particularly important if turns have to be minimised due to limitations of a waterway.

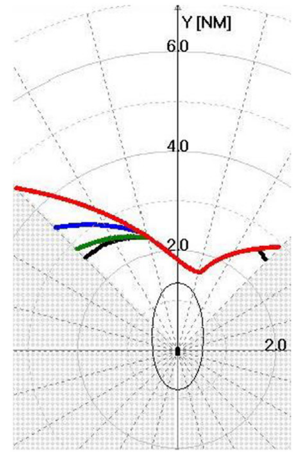

Fig. 15. Action lines for overtaking a target ship, whose relative speed is 12 knots. Assumed are turns of 15° to port without speed reduction (red) or with speed reduced by 3 knots (blue), 6 knots (green) or 9 knots (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

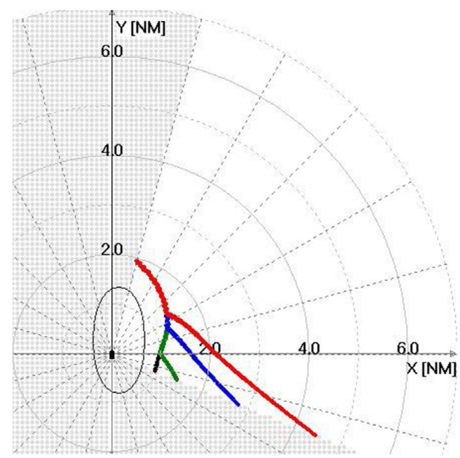

Fig. 16. Action lines for crossing encounter with a target ship, whose true speed is 18 knots. Assumed are turns to starboard by 75° (red), 90° (blue), 120° (green) and 150° (black). No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Discussion and summary of results

The ship, whose model has been used throughout the simulations is very manoeuvrable: a full circulation takes 150 s when turning to starboard and 172 when turning to port. Speed reduction, on the other hand is harder to make for the assumed ship and it takes about 10 min to reduce own speed from 17 to 8 knots. Obviously, the obtained results are affected by the abovementioned dynamics of own manoeuvres. The manoeuvring abilities of the own ship are however to some extent neutralized by the high speeds of both the own ship and the target ships used in the simulations. Therefore roughly similar results may be expected in case of a less manoeuvrable own ship and lower speeds.

It must be also emphasised here, that the presented method checks the effects of all combinations of course change and speed change that are within the limits specified by a user. The optimal combination (the one allowing for the latest action) is always chosen (as already depicted in Fig. 1) and these optimal combinations produce the action distances shown in the figures in Section 5. In general, a combination of course change and speed reduction should always be carefully planned, as simultaneous turn and speed reduction may sometimes cancel each

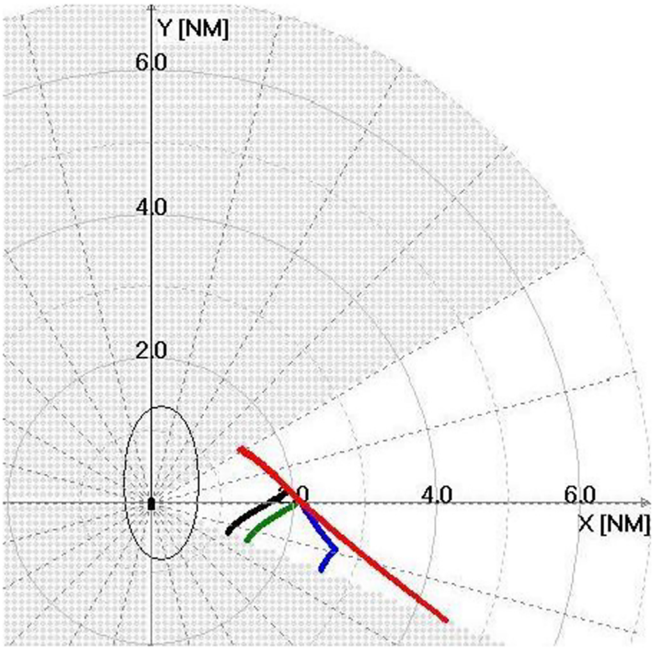

Fig. 17. Action lines for crossing encounter with a target ship, whose true speed is 18 knots. Assumed are turns of 75° to starboard without speed reduction (red) or with speed reduced by 3 knots (blue), 6 knots (green) or 9 knots (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

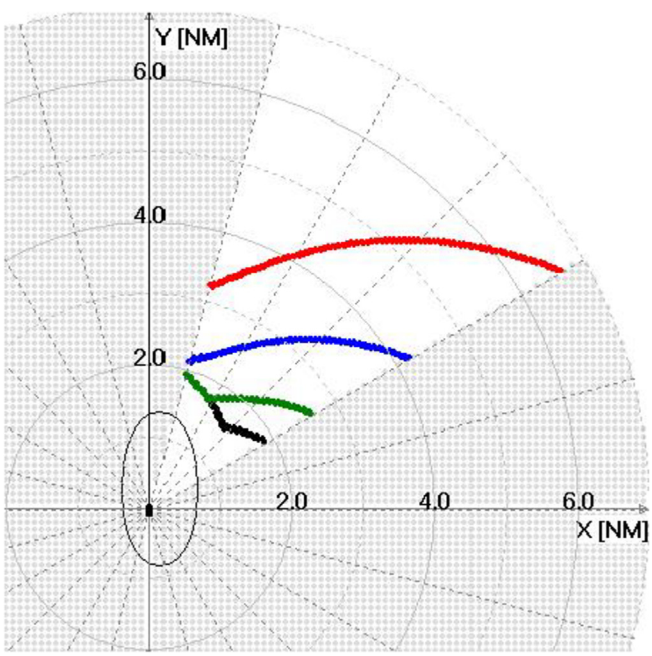

Fig. 18. Action lines for crossing encounter with a target ship, whose true speed is 18 knots. Assumed are turns to starboard by 20° (red), 30° (blue), 45° (green) and 60° (black). No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

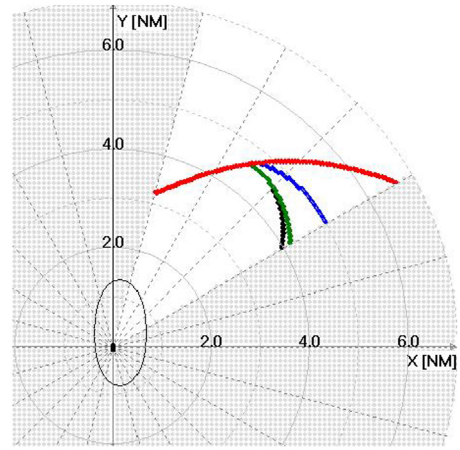

Fig. 19. Action lines for crossing encounter with a target ship, whose true speed is 18 knots. Assumed are turns of 20° to starboard without speed reduction (red) or with speed reduced by 3 knots (blue), 6 knots (green) and 9 knots (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

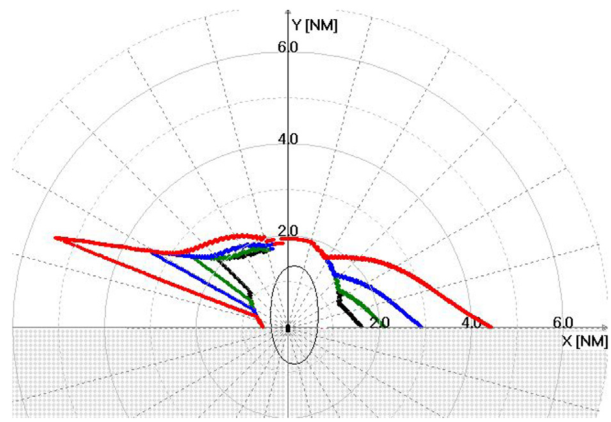

Fig. 20. Action lines for encounter with a target ship in front in restricted visibility. Target ship's true speed is 18 knots. Assumed are turns to starboard by 45° (red), 60° (blue), 75° (green) and 90° (black). No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

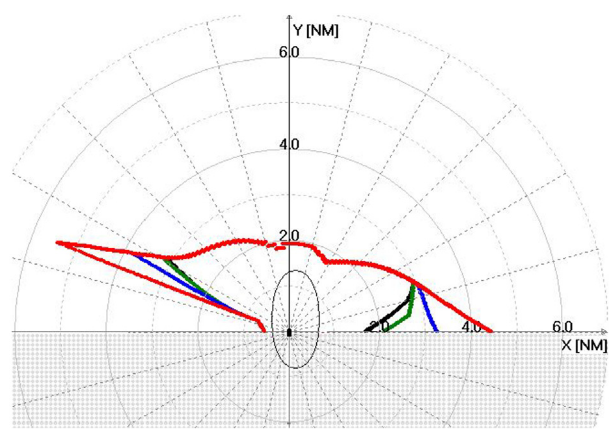

Fig. 21. Action lines for encounter with a target ship in front in restricted visibility. Target ship's true speed is 18 knots. Assumed are turns of 45° to starboard without speed reduction (red) or with speed reduced by 3 knots (blue), 6 knots (green) and 9 knots (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

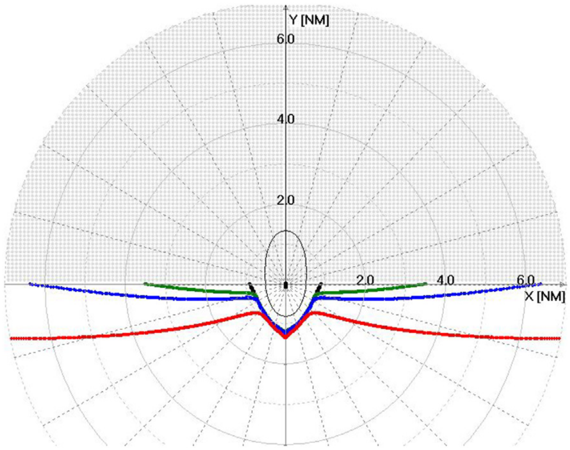

Fig. 22. Action lines for encounter with a target ship behind the beam in restricted visibility. Target ship's true speed is 18 knots. Assumed are turns away from the target ship by 15° (red), 25° (blue), 30° (green) and 45° (black). No speed reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

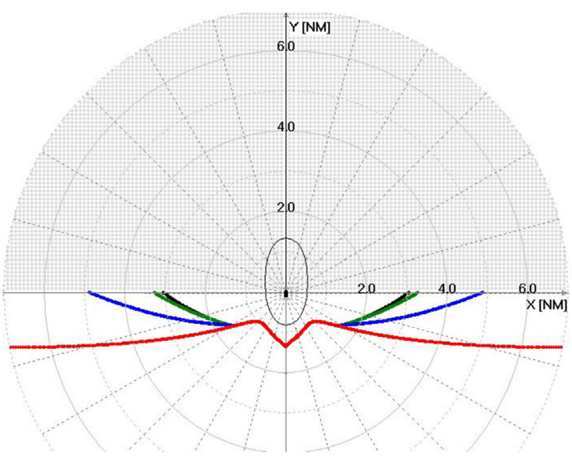

Fig. 23. Action lines for encounter with a target ship behind the beam in restricted visibility. Target ship's true speed is 18 knots. Assumed are turns of 15° away from the target ship without speed reduction (red) or with speed reduced by 3 knots (blue), 6 knots (green) and 9 knots (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

other's effects. A detailed method for choosing a combination of own course and speed in an encounter situation to avoid collision has been presented in (Szlapczynski and Szlapczynska, 2015).

6.1. Discontinuity of action lines around the own ship

The first noteworthy observation concerns the already mentioned discontinuity of the determined action lines. If the action distances are computed for wide sectors around the own ship and COLREGS-compliance is assumed, then action lines will lose continuity in the points where different COLREGS rules start to apply:

- In good visibility the action distances will rise drastically for relative bearings where overtaking (manoeuvres to either side) turns into crossing (manoeuvres to starboard only), as shown in Fig. 6.
- Similarly, in restricted visibility the action distances will greatly rise for target ships observed ahead of traverse (manoeuvres to starboard mean turning towards a target ship), when compared with target ships behind the traverse (manoeuvres away from a target ship, which are more effective), as shown in Fig. 7.

This fact has not been properly investigated before by researchers proposing arena shapes (Davis et al., 1980; Colley et al., 1983) or action zone (Dinh and Im, 2016) and, as evidenced here, it makes a huge difference in the obtained action distances for various bearings around the own ship.

6.2. Head-on encounters

Unsurprisingly head-on encounters have been found the easiest to solve. Even though relative speeds are the largest for head-on, the courses are nearly parallel so a minor alteration of course is usually enough to avoid collision (Hanninen and Kujala, 2012). As a result, the action distances are rather short and speed reduction is neither necessary nor effective in comparison to near-instantly done minor turns. In particular, turns of about 30° allow for very small action distances (Fig. 9) at the still acceptable deviation cost. Also, according to the results, the fact that manoeuvres to starboard only are considered has no significant impact on action distances determined for target ships on starboard.

6.3. Overtaking encounters

Two separate cases of overtaking have been analysed: the first one when manoeuvres to either side are possible and the second, when turns to one side only are feasible due to some outside obstacles or limitations. Despite low relative speeds the first case has been found similar to head-on in that minor course alterations are usually sufficient, even if performed at a short distance from a target ship (Figs. 10, Figs. 11 and 12). For the lowest relative speeds (Fig. 10) or larger turns (Fig. 11), the action lines are very close to the domain's boundary and resemble its shape. For larger relative speeds and smaller turns, the action distance is the shortest in case of target ships straight ahead. Another similarity to head-on encounters is the low effectiveness of speed reduction: it has only been found useful for target ships on more distant bearings to either side and even then the gain is insignificant (Fig. 12).

If manoeuvres to one side only are possible, the action distances are considerably larger (even by 2 NM) when turns have to be made towards target ship (Figs. 13, Figs. 14 and 15). The distances rise with the relative bearings of target ships, except when large course alterations (60°) or speed reductions (by 6 or more knots) are assumed. Speed reductions are useful, when turning towards the target ship, as they can significantly shorten the action distances (Fig. 15).

6.4. Crossing encounters

Crossing encounters cover a great range of relative bearings, so again two cases can be distinguished, depending on whether the target ship's relative bearing is up to 60° to starboard or more than that. In the first case turns of up to 45° are sufficient for the action distances of about 2 NM (Fig. 18). Those turns can be even smaller if accompanied with a speed reduction (Fig. 19). In the second case, especially for target ships behind the traverse, the action distances are much longer. If the distance between ships gets shorter than 3 NM, than a truly huge turn is necessary (120–150° as shown in Fig. 16) or a combination of a large turn (e.g. by 75°) and speed reduction (by about 6 knots in Fig. 17). It is particularly interesting and counter-intuitional that speed reduction, which was practically useless for encounters with target ships ahead (head-on, overtaking and the previous case of crossings) becomes essential for late actions in crossing encounters with target ships behind the traverse. However it is worth repeating here that in encounter situations a combination of a turn and speed reduction manoeuvre should always be simulated first before being performed: simultaneous manoeuvres of course and speed changes may occasionally cancel each other's effect.

6.5. Encounters in restricted visibility

COLREGS recommend turning away from a target ship when being overtaken and it makes this scenario much easier to solve. For moderate target ship's speeds (which can be expected in this case), a turn of up to 45° is enough to avoid violating ships' domains when being overtaken (Fig. 22). Even smaller turns of the own ship (down to 15°) will still be sufficient if they are accompanied by an appropriate speed reduction – the largest for target ships near traverse (Fig. 23). As for encountering a target ship in front, Rule 19 of COLREGS instructs navigators to turn to starboard rather than port. This makes it relatively hard to avoid faster target ships approaching from port (Fig. 20). If a manoeuvre is performed early, a turn up to 45° may be sufficient, especially if it is combined with a speed reduction. However, late manoeuvres (at a distance of 2 NM or less) may require turns by more than 60° (Fig. 21). In general the situation of meeting a target ship in front of the own ship in restricted visibility may be considered hard, but still easier to solve than some extreme cases of crossing in good visibility, when a fast target ship is behind the traverse. Fortunately, in restricted visibility COLREGS instructs navigators to turn away from a target ship abaft the beam, which eliminates the necessity of most inconvenient manoeuvres and allows for smaller action distances or smaller turns in case of target ships approaching from behind.

7. Summary and conclusions

The paper introduces a method of determining action distances in give-way situations, when the own ship should perform a specified manoeuvre, including speed reduction if necessary. The method uses a ship domain and related parameters as criteria for detecting potential close quarters situations. It takes into account own ship's dynamics and simulates own ship's movement throughout encounter situation applying robust numerical algorithms and author-derived analytical solutions. Owing to all of the above, the method combines high accuracy with a low computational complexity, which allows for fast and precise real time computations on board of a ship.

The method has been applied in a series of extensive simulations to determine action lines around the modelled own ship for a wide array of encounter scenarios. Chosen scenarios cover: head-on, crossing and overtaking situations; manoeuvres limited to course alteration and those combining turns with speed reduction; open or confined waters and finally – good and restricted visibility. In the course of the simulation experiments it has been revealed that the shape of action lines around the own ship largely differs from shapes presented in previous works on this subject. The biggest difference is the discontinuity of the action lines, which is bound to appear if COLREGS are to be obeyed. Some other anomalies and counter-intuitional results have been obtained. These include, among others the fact, that one of the most dangerous encounter situations may be crossing, when a stand-on target ship is approaching fast from behind the traverse. Rule 15 of COLREGS instructs the navigators to avoid crossing ahead of a target ship, which practically means that a turn to starboard – towards a target ship should be made. For some combinations of ships' positions, courses, and speeds this particular manoeuvre may require a large action distance or (if the distance is already too small) reducing own speed significantly. Similar, risk-revealing results have been observed for simulating encounters in restricted visibility, when a target ship on starboard side is forward of the beam but very close to traverse. Rule 19 of COLREGS recommends manoeuvres to starboard in that case, which again may be problematic and require early manoeuvre.

Considering the popularity of ship domains as safety criteria in collision-avoidance research, it is essential to specify when exactly a navigator has to act to avoid domain's violation. And it is perhaps equally important to point out situations when earlier than usual or counter-intuitional actions should be taken. The paper addresses both issues, though presented simulation results are obviously dependant on the dynamics of a ship, which has been used in the simulations. Further research, utilising a larger number of ship models, should be performed to allow for additional and more far-fetched statements concerning the subject investigated here.

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